Secondary Processes Associated with Landslides in Vietnam

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Abstract. Landslides are one of the most dangerous geohazards in tropical monsoon countries. Various impacts of landslides on lives and property not only result from the destruction of the down movement itself but is also due to secondary effects including the formation of landslide-dammed lakes and the generation of tsunami-like waves. This paper presents a study on secondary processes associated with landslides hazards in Vietnam through site surveys, air photos, and data collection and analysis. First, the paper reports a comprehensive investigation of the study on landslides and their consequential hazards in recent 30 year. Then, three typical cases of landslides in the Van Hoi reservoir, Khanh waterfall, and Song Bung hydropower reservoir are characterized in terms of geological features, causes, and sliding mechanisms. Besides, landslide hazard assessment for disaster risk reduction is briefly discussed. Study results significantly indicate that heavy rainfall is the main trigger for landslides and its cascading effects (i.e., river damming and dam breach, and landslide-generated waves). While the geological structures of high fractured, deformed, and weathered rocks are the main preparatory factor of the landslides. Landslides associated with secondary hazards has been rarely analyzed in Vietnam, this study will, therefore, bring a significant understanding for planning and management of multiple disaster risk in the river-hillslope system.

Keywords: Landslides · Secondary processes · Dam reservoir · Cause · Mechanism · Vietnam

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1 Introduction

Landslide phenomena are globally one of the most frequent natural hazards that cause a lot of significant damage to people and properties [1, 2, 3]. The human and economic losses result from the destruction of the mass movement of earth materials itself and the potential effects of its secondary processes that include the dam formation due to river blockage and the generation of tsunami-like waves [4–6, 7, 8]. The cascading effects to upstream and downstream areas due to the secondary hazards are presented in detail by Korup [8]. In river valleys, the large amount of the sliding materials can completely or partially fill the rivers to create natural reservoirs behind the landslide dams [4–8]. If the water table due to the impoundment process increases; the landslide dam may be highly vulnerable to instability or breaching because of various phenomena of upstream inundation, dam erosion phenomena, and the continuous effects overtopping and piping failures [6, 8]. The landslide dam breach associated with debris flows and outburst flood will pose serious hazards to downstream communities. While upstream reservoir bank slopes saturated by impounded water are prone to the failure to generate impulse waves and overtop that may cause cascading effects [4–6]. Several historical records of catastrophic landslides associated with secondary processes, including dam formation, landslide-generated waves and flash floods, are presented in Table 1.

Table 1. Historical records of catastrophic landslides associated with its secondary effects over the world

No	Event	Time	Country	Casualties	Ref
1	The overtopping and flooding due to the landslide dam failure	1786	China	100,000	[9]
2	The failures of three landslide-dammed lakes and its flooding	1933	China	20,000	[10]
3	Landslide lake outburst flooding and landslide dam failures in Uttarakhand	2013	India	5,000	[11]
4	The landslide induced waves in the Vajont reservoir	1963	Italy	2,000	[12]
5	The Shiaolin landslide dam and severe outburst flood event	2009	Taiwan	400	[13]
6	The Jure landslide dam and its dam overtopping and failures	2014	Nepal	156	[14]
7	The large-scale landslide in the Canelles reservoir	2006	Spain	-	[15]
8	The Qianjiangping landslide in the Three Gorge Reservoir (TGR)	2003	China	24	[16]
9	The large-scale deep-seated landslide in the Aratozawa reservoir	2008	Japan	-	[17]
10	The Shuping and Outang landslides in the TGR	Active	China	-	[18]

Landslides and its secondary processes have been well studied by many authors. First, hazard assessment of landslide dams by an investigation of various effects resulting from dam formation and failure, (e.g., backwater inundation, dam breaches, outbursts of impoundment waters, downstream flooding, debris flows, and long-term river aggradation) has been conducted by [4–6, 8, 19–27]. In this point of view, heuristic, deterministic, statistical, and inventory approaches are employed to identify the risks and explore their mechanisms [1, 28]. Tien [28] present that numerical models using the heuristic method were often carried out by trial-and-error analyses (e.g., the LSFLOW model by Sako [29] and a distinct element method (a two-dimensional (2D) particle flow code (PFC) by Li [30]). Deterministic approaches are commonly based on slope stability analysis using soil properties [18, 31]. For statistical methods, regression analysis is used to assess the susceptibility of the landslides and its sequential effects [4, 8, 24, 26]. Inventorying landslide dams for building regional and global databases of landslide dams is the most common approach for qualitative identification of landslide dam hazards [32]. There are several large datasets of landslide dams in the world, which consist of 31 cases in Switzerland; 232 landslide dams in New Zealand; 300 landslide dams from the Alps to the Southern Apennine and Sicily areas; and a complete and unique inventory of 828 landslide dams triggered by May 12, 2008 Wenchuan earthquake in China [28, 32]. In these studies, several geomorphological indexes, which integrate two or more morphological parameters of the landslides (e.g. the volume, depth, velocity of mass movement) and the river valley (e.g. catchment area, valley width, slope parameters), were also proposed to evaluate dam formation and stability for its risk assessment and management [28]. Notably, modeling approaches, including deterministic models, an empirical model, numerical simulations, or laboratory and field experiments have been widely employed to evaluate secondary hazards of dam formation, backwater inundation, dam failure, dam-breach floods, etc. [22, 25, 28, 33, 34].

Secondly, slope failures into reservoirs may create impulse waves that pose the most disastrous hazards to dam structures and downstream areas. Landslide-induced waves have been studied by many authors worldwide, e.g., Panizzo [35]; Biscarini [36]; Ataie-Ashtiani and Yavari-Ramshe [37]; and Glimsdal [38]. Hazard assessment of landslide-induced waves aims to evaluate some parameters such as the velocity, height and run-up of waves, the run-up impact areas, and time of the propagation. These parameters are investigated from mathematical theories [39], physical model experiments [35, 40], and numerical simulations [36]. As for numerical models, the authors carried out their studies based on Boussinesq equations [41] and Reynolds-averaged Navier–Stokes (RANS) equations [42].

Vietnam has a mainland area of 330,000 km^2, of which 70% is mountainous. Vietnam, with a 3,260 km long coastline, located in the eastern margin of the Indochinese peninsula that is strongly affected by typhoons and tropical depressions. In the period 1961–2010, the country was on average hit by about 12 typhoons per year which always brought heavy rainfall and floods [43]. Besides, the complexity of topography, geology and monsoon climate with extreme rainfall makes the country extremely prone to geo-hydrological hazards such as landslides and flash floods. Landslides frequently take place on cut slopes during tropical cyclones in which rainfall plays the role of a triggering factor [27, 44, 45, 46]. In recent decades, landslides and flash floods have become very intensive and destructive, causing huge losses of life and property [47]. The damages to the transportation system due to landslides and floods were estimated at 100 million USD per year [48]. In mountainous regions, landslides may block the river channels to form natural reservoirs that are vulnerable to failure to induce flash floods while the sudden falling of the landslides into the reservoirs can generate displacement waves inducing downstream flash floods and overtopping. Although these secondary hazards of landslides have been reported many times by the media and authorities, landslides associated with secondary hazards have rarely addressed for proposing disaster risk reduction measures. This paper, therefore, aims to firstly review the episodes of landslides in association with secondary hazards, and then to present preliminary results on a study of three landslide cases in Vietnam through site surveys and the analysis of air photos and data collection.

2 Secondary Processes Associated with Landslides in Vietnam: A Review

In recent years, landslides, mudflows and flash floods frequency occur in the mountainous regions, causing serious and extensive damages to lives and properties in Vietnam. From 2000 to 2015, landslides, mudflows and flash floods happen every year with a total of 250 events, killed 779 people, and caused a huge economic loss [49]. Flash floods are mainly induced by heavy rainfall in the large watersheds with steep channels in the Northern and Central regions and frequently accompanied by landslides [47, 50]. The provinces, which are the most frequently affected by landslides, mudflows and flash floods are such as Lai Chau, Lao Cai, Ha Giang, Yen Bai, Son La, Hoa Binh, Thanh Hoa, Nghe An [13, 51]. Many landslides and flash floods, which simultaneously were induced by heavy rainfall, were recorded in Vietnam, e.g. the 1996 flash flood due to landslide dam breach killed over 89 people in Lai Chau [51]; the 2005 flash flood claimed 50 people in Van Chan, Yen Bai; the flash flood caused 88 deaths in Lao Cai in 2008; the Ban Khoang flash flood and extensive landslides killed 11 people in 2013; the Sa Na outburst flood and landslide disaster claimed ten casualties in 2019 (Table 2). As can be seen in Table 2, many flash floods occurred as a cascading effect due to the formation and failure of landslide-dammed lakes. The landslide dam breach causing the 1996 Muong Lay flash flood has been so far one of the worst sediment-related disasters in Vietnam. The landslide formed a natural lake in 1 km length at Nam He river. Due to continuous heavy rainfall, the landslide-dammed lake failed to release a flash flood with a flooding water depth of 15 m, which swept away the Muong Lay town. This disaster claimed 89 people and completely demolished Muong Lay town. The town was forced to relocate to a new site after the disaster. In most of the cases, landslide dams are formed in the regions where the terrain is narrow valleys bounded by high and steep slopes [50–52]. This kind of regional setting is mainly the preparatory condition for blocking river valleys to form landslide-dammed lakes in Vietnam. In this regard, narrow valleys facilitate the river damming even a relatively small volume of the landslides [4, 28].

On 26 September 2012, a landslide with a total volume of 10,000 m^3 completely blocked the Coc stream to form a natural reservoir in Ta Phoi commune, Lao Cai city (Fig. 1). The landslide-dammed lake had a maximum depth of 20 m, 25 to 30 m wide

Table 2. Recorded history of some flash flood and landslide events triggered by heavy rainfalls

No	Time	Location	Flash floods due to dam breach	Death	Ref
1	27 Jul. 1991	Son La city	x	32	[53]
2	27 Jul. 1991	Mai Son, Son La	x	16	[53]
3	Aug. 1996	Muong Lay, Lai Chau	x	89	[51]
4	Sep. 2005	Van Chan, Yen Bai	-	50	[54]
5	5 Jul. 2007	Moc Chau, Son La	-	10	[53]
6	8 Aug. 2008	Lao Cai city	-	88	[47]
7	26 Sep. 2009	Mai Chau, Son La	-	35	[53]
8	26 Apr. 2010	Ha Giang city	-	5	[47]
9	14 Aug. 2010	Van Yen, Yen Bai	-	7	[47]
10	31 Aug. 2012	Bac Ha, Lao Cai	x	11	[47]
11	4 Sep. 2013	Ban Khoang, Sapa, Lao Cai	x	11	[55]
12	5 Aug. 2016	Bat Xat, Lao Cai	-	11	[49]
13	3 Aug. 2017	Nam Pam, Son La	-	15	[49]
14	3 Aug. 2017	Mu Cang Chai, Yen Bai	x	14	[49]
15	3 Aug. 2019	Sa Na, Thanh Hoa	x	10	[49]

Note: Mark “x” presents the landslide dam formation and breach to generate flash floods

with an impoundment volume of 1.0 million m^3. The upstream inundation area was estimated at 0.2 km^2 [56]. The dam formation and its potential outbreak threatened to 400 households and a large area of agricultural land downstream. The dam failed on the night of 26 September when urgent countermeasures to drain out impounded water were conducted by the Lao Cai government. Therefore, there was no sudden failure of the landslide dam and outburst flood that could cause a severe disaster to downstream communities. In July 2013, a landslide dam reservoir was created due to a blockage of the Muong Hum stream in Bat Xat, Lao Cai city [52]. The dam breached in a short time, it might be because a small volume of the landslide material was eroded by a large volume of impounded water. Notably, about 1:30 AM on 12 October 2017, a landslide associated with mudflows severely destroyed Khanh village in Phu Cuong, Tan Lac, Hoa Binh province. The catastrophic disaster killed 18 deaths, buried 10 houses and partly damaged to other tens of houses and local roads (Fig. 22) [57]). The landslide was preceded by local failures and ground settlements in the village just one day before, but no evacuation and any measures were forced to prevent and mitigate its potential impacts [58].

In Vietnam, landslides not only dam the river channels to form natural lakes, but also the falling of the landslide body into the water can generate displacement waves. Two events of landslide-generated waves were recorded in the recent years, including impulse waves generated by a large deep-seated landslide in the Van Hoi reservoir dam

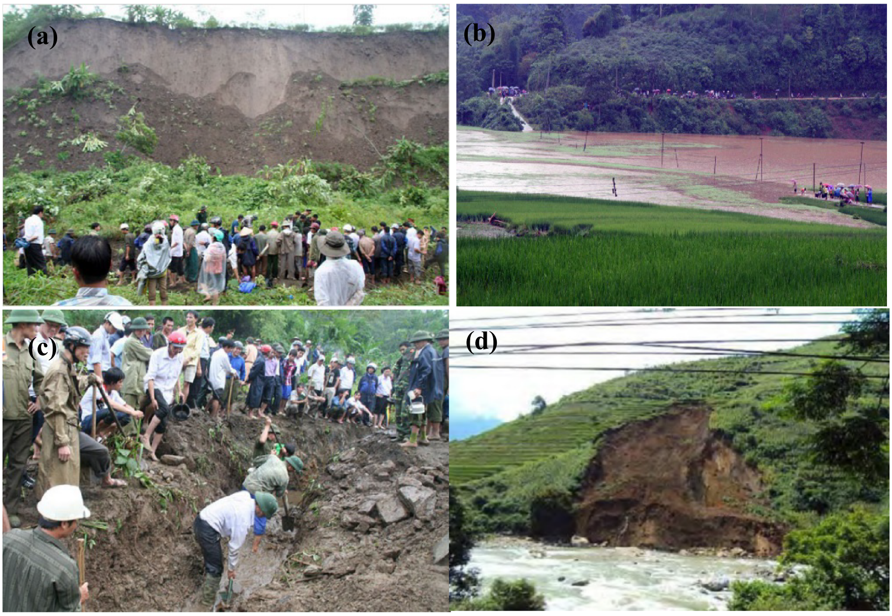

Fig. 1. Landslide dam formation in Ta Phoi, Lao Cai (photos from Radio The Voice of Vietnam - VOV): (a) Landslide body blocked the Coc stream; (b) Upstream inundation due to landslide dam formation; (c) Countermeasures to drain out impounded water; and (d) Landslide dam after the breach at Muong Hum, Bat Xat, Lao Cai [52].

in 2016 and landslide-induced water waves in Truong river. In the latest event, the landslide was induced by extremely intense rainfall with cumulative 48-h precipitation of 947.2 mm (Fig. 3). The landslide produced a soil volume of 150,000 m^3 and its downslope movement instantly generated a surge wave of 8.5 m high across the Truong river destroyed 6 houses, claimed 1 person, and injured 3 others in the opposite slope in Tra Giang commune, Bac Tra My district, Quang Nam province (Fig. 4, [59]). Duc et al. [59] studied the landslide and its impulse wave by using numerical models of LS-RAPID and LS-TSUNAMI developed by Sassa et al. [60, 61] for landslide simulation and landslide-tsunami simulation, respectively (as shown in Fig. 5). The numerical simulations of Tra Giang landslide and landslide-generated tsunami, which were first applied in Vietnam, were well verified to interpret the entire processes of the landslide and its consequential event.

3 Case studies

3.1 Landslide in Van Hoi reservoir dam

Located in An Tin commune, Hoai An district, Binh Dinh province, Van Hoi reservoir with a storage capacity of 14.5 million m^3 is one of the very big irrigation reservoirs and plays a vital role in agricultural development in Vietnam. Recently, landslides frequently take place in the rainy season, which seriously affect the safe operation of dam facilities

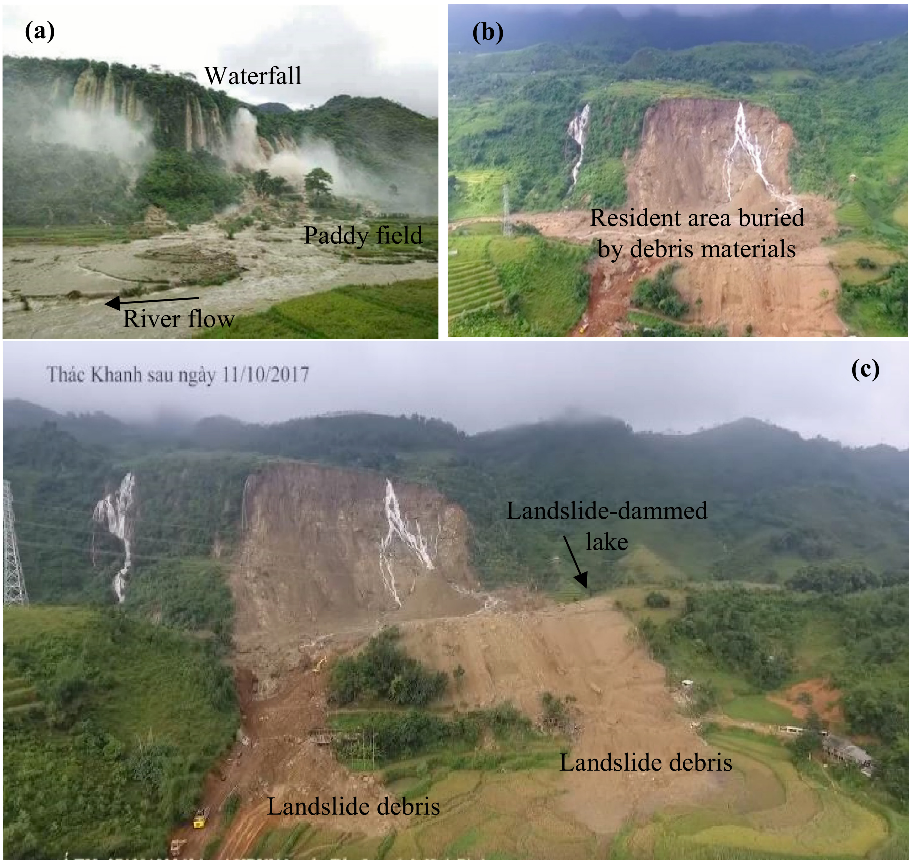

Fig. 2 (a) Photo of Khanh waterfall before the failure by a local resident [37], and (b, c) landslide and its impacts to resident areas in Khanh village (photos from a video by Tan Lac Radio Television [62]).

and threaten the lives of thousands of households downstream. On 17 December 2016, heavy and prolonged rainfall triggered several landslides on the upstream slope opposite the dam facility. The biggest landslide entered the lake and generated high-water waves of about 20 m which extensively destroyed the dam structure and its facilities before causing spills over the dam crest and operation house (Fig. 6) [64]. This serious disaster has never happened in Vietnam.

Precipitation data before and after the landslide occurrence monitored at Hoai An rain gauge station in Tang Bat Ho district, approximately 6 km from the reservoir site, are shown in Fig. 7. It shows that the landslide was triggered by heavy rainfall. The accumulative rainfall prior to the sliding was over 800 mm in December 2016.

Field surveys and UAV investigations were carried to examine the causes and characteristics of the landslide. An orthomosaic photo of the Van Hoi reservoir that was generated by a series of aerial photos is shown in Fig. 8a. The landslide occurred on the slope that densely covered by a forest. The slope failed at elevation 196 m and deposited

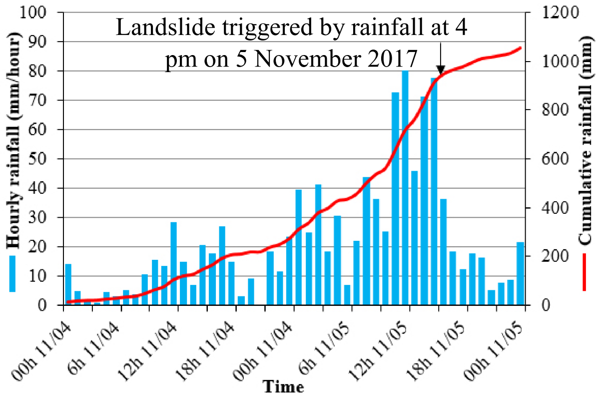

Fig. 3. Landslide occurrence time and hourly precipitation data at Tra My meteorological station.

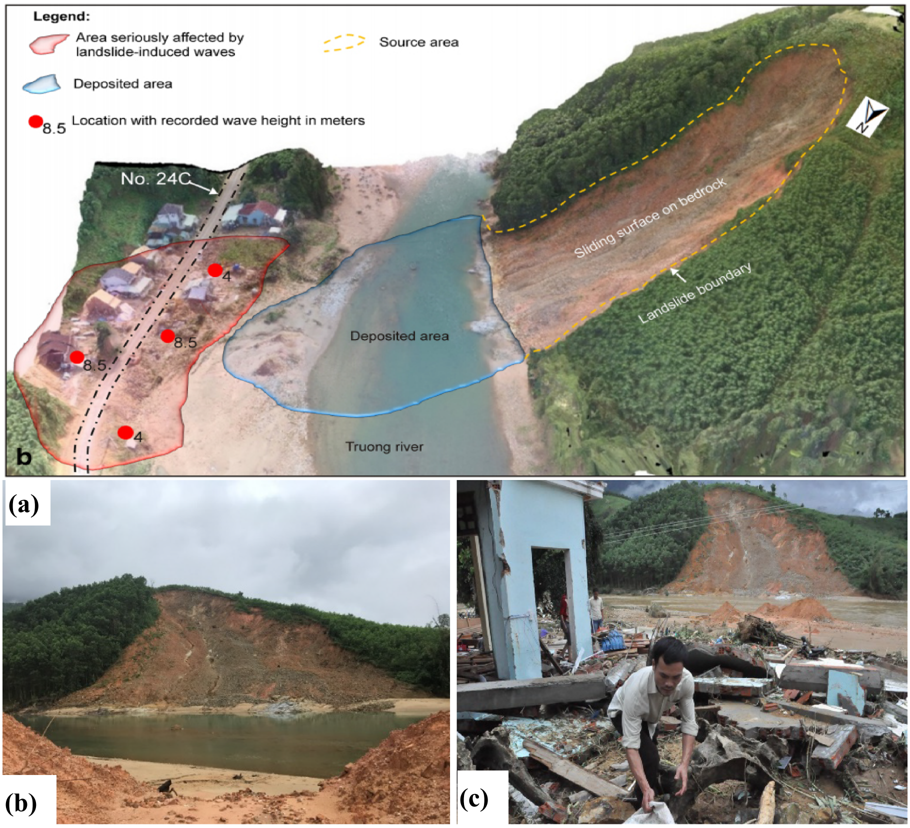

Fig. 4. (a) 3D view of the Tra Giang landslide [59]; (b) Landslide after sliding (photo by Dinh Thi Quynh); and (c) Collapsed houses due to tsunami waves [63].

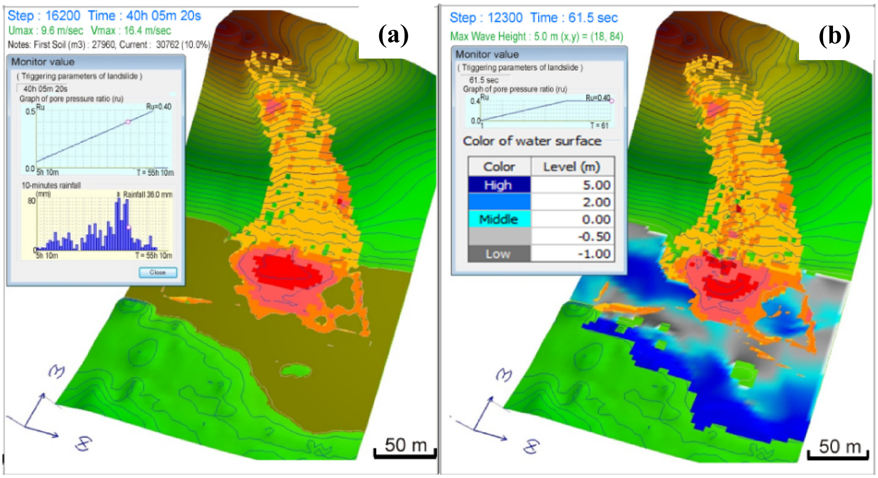

Fig. 5 (a, b) Simulations of rainfall-induced landslide and landslide-generated tsunami [59].

Fig. 6. Damages to the Van Hoi dam and its facilities due to landslide-generated waves (Photo courtesy by Do Canh Hao).

at the reservoir floor at an elevation ranging from 25–28 m. The displaced mass has a length of about 510 m and a width ranging from 120 m at the top and 280 m at the toe. The landslide occurred on the slope of 21°. The displaced materials of the slope entirely lied on the floor of the lake and severely reduced the operating capacity of the dam (Fig. 8b). Preliminary results of site surveys show that the landslide slid along the bedrock of granite rocks and the landslide deposits mainly consisted of weathered granite materials of sand, silty sand, clayed sand, and clay (Fig. 8c).

3.2 Landslide in Khanh waterfall

In Phu Cuong, Tan Lac, Hoa Binh province, a large portion of the Khanh waterfall slid down on 12 October 2017 and buried a large area in Khanh village (Figs. 9 and 10). The landslide is geologically characterized by Dong Giao and Co Noi Formations with limestones, sandstone, tuffaceous siltstone, clay shale, and marl. The area is located in

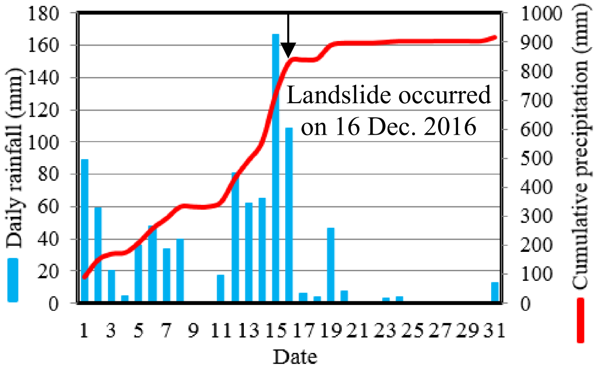

Fig. 7. Daily rainfall in December 2016 and landslide occurrence.

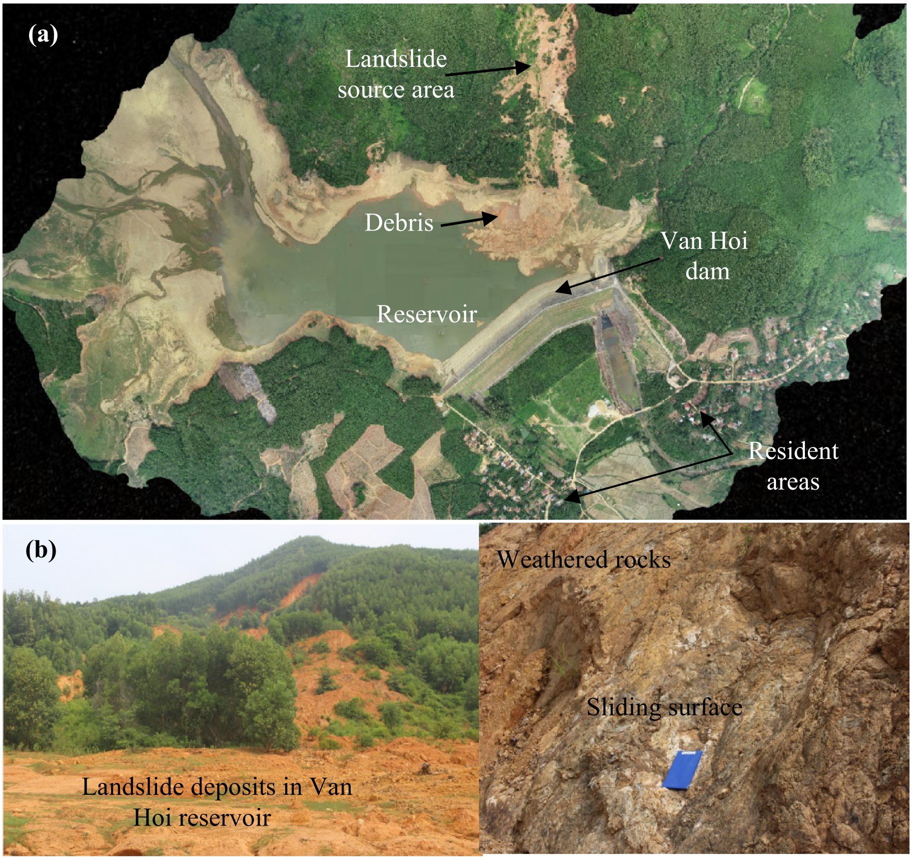

Fig. 8. (a) Orthomosaic photo of the Van Hoi reservoir and its landslide; (b) Van Hoi reservoir and landslide in June 2018 and October 2019; (c) Sliding surface exposed in the flank of the landslide.

the North-West of Vietnam, which is strongly affected by active faults in the east-west direction [65]. Some lineaments as active faults can be delineated on satellite images around the Khanh village slope in Fig. 9b. Based on the site survey, a geological slope profile of the landslide was created in Fig. 9c. It presents that the landslide area consisted of weathered materials of limestones in Devonia-Slurian Age and sedimentary rocks. The slope slid along the sliding surface which was the geological boundary of sedimentary rocks and limestones. The slope with a height of 120 m and width 200 m was triggered by heavy rainfall. The cumulative hourly precipitation that triggered the landslide was 437 mm between 9 to 11 October 2017 (Fig. 11).

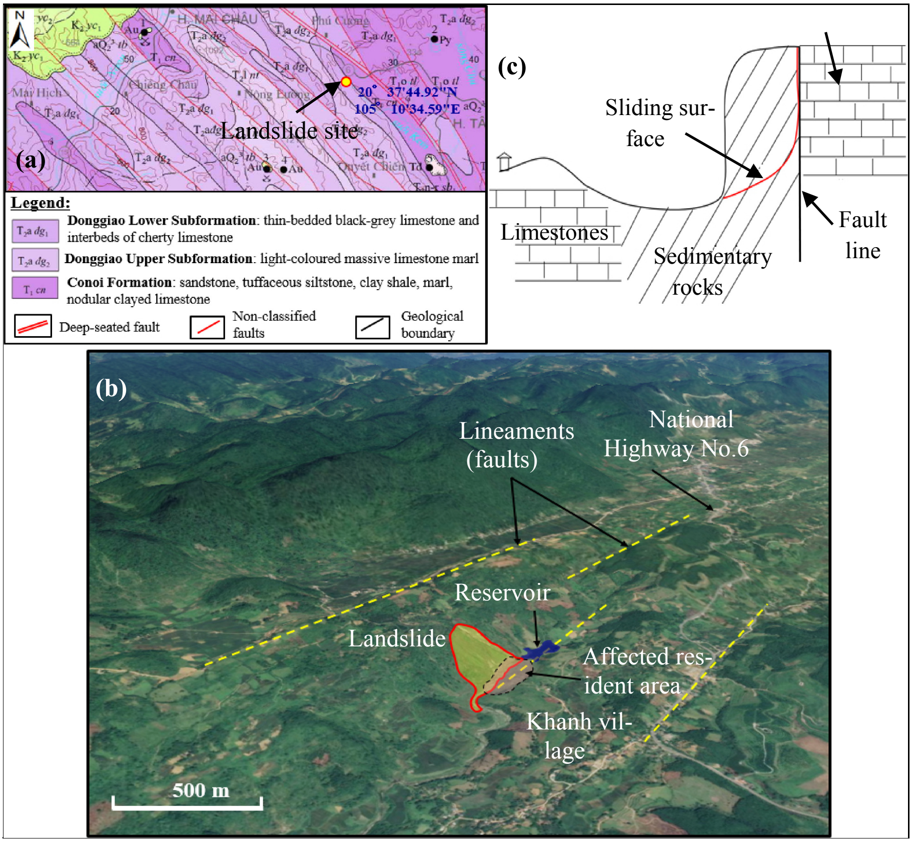

Fig. 9. (a) Landslide location and its geological settings [65], (b) 3-D view of Khanh waterfall area, and (c) geological slope profile of the landslide

We conducted a site survey in January 2018 to study geological and morphological features and sliding mechanism. Topographical and geological features of the landslide area is presented in Fig. 11. The landslide was characterized by a compound type initiated by rockfalls and then the slope failed as earth fall and earth slide. A rapid massive movement as a debris flow was then formed along the river valley with a long distance of 350 m. The landslide debris moved down and blocked the stream to form a small natural lake with an impounded water volume of about several thousand cubic meters (Fig. 11a and b). Site investigations indicated that the sliding surface mainly lied on an active fault in a northwest-southeast direction. The landslide debris consisted of materials of strongly fractured, deformed and weathered limestones (Fig. 11c, d, and e). These features of limestones are due to the strong influence of active tectonic faults in the study area. The geological features of fractured and sheared rocks favored the water infiltration deeply into the slope strata to generate the high pore water pressure that triggered the sliding. As can be seen in Fig. 11, the water always flowing out from the top mountain indicates the abundant condition of water runoff and groundwater table in the study site. This factor is also a favorable condition for accelerating both physical and mechanical weathering processes of sedimentary and limestone rocks in the landslide area.

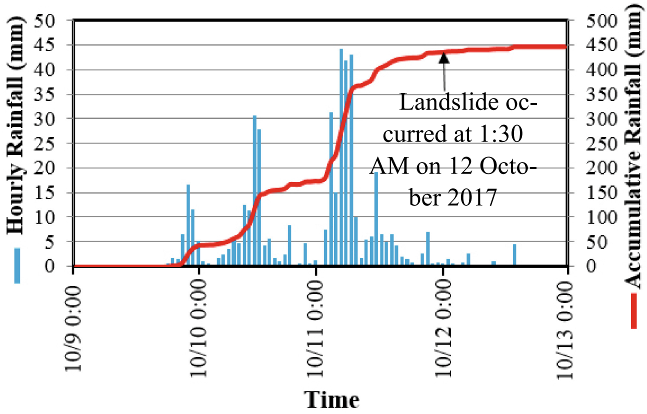

Fig. 10. Landslide occurrence time and hourly rainfall data at Mai Chau meteorology station.

3.3 Landslide nearby Song Bung hydropower reservoir No. 5

A large-scale deep-seated landslide near Song Bung No. 5 Hydropower is one of the most dangerous hazards in Quang Nam province. The landslide is located near the national highway No. 14 and on the left bank of the Song Bung reservoir (Fig. 12a). Landslide characteristics were presented on the topographic map using the method of aerial photo interpretation (Fig. 12a, b, [66]). The boundary and main scarp of the landslide are apparent from aerial photos. The landslide is about 1,000 m in width and 1,500 m in length, extending from the top of the mountain to the shoreline of the reservoir (Fig. 12b, c). The landslide is reactivated to move down, therefore, many cracks have been developing along the road and retaining wall (Fig. 12d). In the case of sliding, the landslide can block the stream to form a dam on the upstream of the reservoir or mass movement falling the water body can induce impulse waves and overtop on the dam.

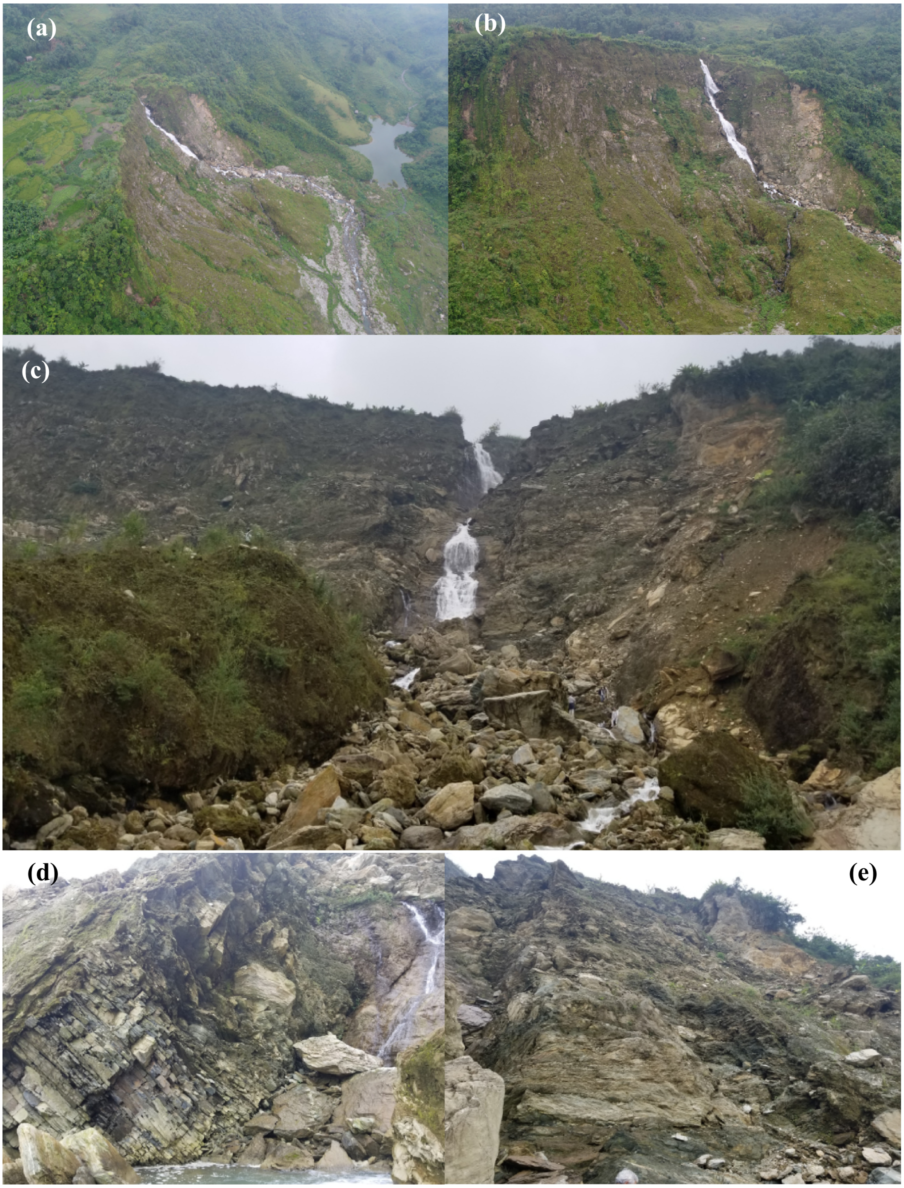

Fig. 11. (a) Top-view of the landslide at Khanh waterfall; (b) Closed-view of the sliding surface; (c) Head scarp and main body of the landslide, and (d, e) Landslide strata with deformed, fractured, and weathered limestones.

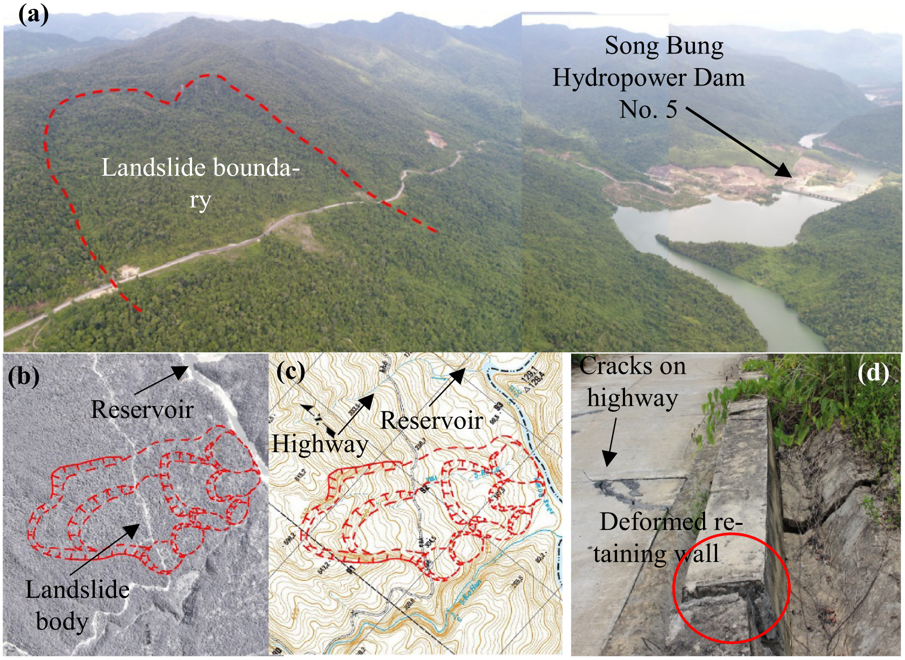

Fig. 12. (a) Overview of the landslide by UAV photos; (b, c) Aerial photo and topographic map with the landslide scarp and boundary [66]; (d) Cracks on retaining wall and highway due to sliding.

4 Discussion and Conclusion

Landslides associated with secondary processes have severely caused damages to socio-economic infrastructure and human living throughout the world. Landslide dam formation and landslide-induced waves have rarely addressed so far in Vietnam, therefore, this paper presenting a literature review on the study of landslides and its secondary hazards is helpful not only for understanding the landslides and its secondary processes but also for disaster risk reduction and disaster preparedness. It shows that landslides and flash floods frequently co-occur during rainfall and these two geo-hydrological hazards cause a lot of human and economic losses. Flash floods were recognized as consequential effects of the failure of landslide dams. Landslides associated with river damming have studied since the 1990s and the 1996 Muong Lay flash flood and landslide disaster presented by Minh et al. [51] has documented to be one of the most disastrous cascading geomorphic events in Vietnam. Based on an investigation of various cases, it indicates that the phenomena of landslides followed by river blockages often take place in the narrow channels and steep slopes in the North and Central region of Vietnam. These features are in agreement with previous studies. In the study areas, geological features of fractured, deformed, and weathered rocks are one the most important preparatory conditions for the landslide occurrence. While heavy rainfall is the main trigger of the landslides in Vietnam, which is commonly characterized by high intensity and a short-time period.

Specifically, rainfall triggered the Truong Giang landslide and Khanh waterfall landslide are very extreme.

Tsunami-like waves generated in the Truong river and Van Hoi reservoir are specific and uncommon in Vietnam. In this study, three cases of landslides in association with secondary hazards, e.g., of dam formation (at Khanh waterfall and in Song Bung No. 5 reservoir) and landslide-generated waves (in Van Hoi reservoir), are briefly presented through site investigations, aerial photos, and data analysis. The problems of landslides and their hazards in dam reservoirs have been outlined as an increasingly considerable challenge during the building and operation periods. However, this kind of research topic has still been under development, particularly the investigation of its sliding mechanisms has not been conducted. Therefore, it is imperative to study the initiation mechanism and processes as well as to assess the landslide hazards in Vietnam. The understanding of the mechanisms and processes of landslides and its secondary hazards are very crucial for safely planning and managing the dams and their reservoirs.

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